

CHAPTER 21: ADVANCED CONCEPTS

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Before there is a funded space mission, there must be a present need for the mission. Space science and exploration are expensive, and without a well-defined and justifiable need, no one is going to commit significant funding for any space endeavor. However, as discussed in Chapter 1, applications of space technology are many and broad, hence there are many ways to determine and establish a mission need.

Robotic science missions are justified by their science return. To be selected for flight, questions like these must be addressed: What is the science question that needs answering, and will the proposed mission be the most cost-effective way to answer it? Why does answering the question require an expensive space flight, instead of some ground-based alternative? If the question can only be answered by flying in space, then why is this approach better than other potential approaches? How much will it cost? And is the technology required to answer the question “in hand” and ready to use? If not, then how much will it cost and how long will it take to mature the technology to a usable level?

There are also many ways to justify human exploration missions, including science return, technology advancement, as well as intangible reasons, such as “national pride.” Nonetheless, many of the questions that need answering, are similar to those for robotic science missions: Where are the people going, why, and will the proposed mission be the most cost-effective way to get there? What is the safest method to achieve the goal? How much will it cost? And is the technology required to get

there and keep the crew alive “in hand” and ready to use? If not, then how much will it cost and how long will it take to mature the technology to a usable level?

Another reason for some groups sending spacecraft into space is for profit.

Telecommunications, geospatial imaging, and tourism are examples of proven, market-driven space missions and applications. For this specific set of users, the outstanding questions include: What is the product or service? Who will buy it? How can it be profitable? What is the most cost-effective solution to fielding the product or service? And, of course, is the technology in-hand or is there advanced development required?

In order to answer these questions, the responsibility falls to a specially-skilled set of engineers and scientists who understand how to assess the readiness of new technologies. This is a process of defining preliminary mission requirements, and the methodologies for assessing multiple candidate mission implementation scenarios against each other leading to a point design for cost assessment, management review and sometimes approval to go into development. This chapter will describe and discuss these advanced concept assessments.

An advanced concepts team

The specific skill mix and organization structure of an advanced concepts analysis team will vary with separate organizations. Some organizations will have a dedicated team of discipline engineers skilled in making high level, rapid turnaround concept studies funded and available when new analyses are required. Other organizations maintain only a core set of advanced concept managers, with discipline expertise obtained by “buying it” from elsewhere within the organization, as specific studies

need to be performed. Either approach has been proven successful; the key is the attitude and training of the individual team members.

A successful space system advanced concepts analysis team will have experts in the following fields engaged in studies, as their skills are needed:

- **Study Manager:** The primary interface with the customer or the innovator. This is the person that understands the requirements and can turn these requirements into a study plan that includes a schedule with interim and final study products clearly defined. The Study Manager also develops the budget and staffs the team with the appropriate discipline experts required to complete the assigned task. This person is also responsible for documenting the results of the analysis and providing it to the customer. It is also desirable for this person to report the results at a relevant technical conference or in a journal article, as appropriate.
- **Lead Systems Engineer:** This is ideally an experienced engineer who has seen at least one advanced concept from the idea phase through hardware development or spaceflight. It is their responsibility to make sure that the study products are wholly integrated, that they are internally consistent with all the study's ground rules and assumptions, and that there are no unforeseen system-level impacts resulting from any single team member's technical analysis.
- **Discipline Engineers:** These are the engineers who actually perform the technical analysis that is the basis of the advanced concepts study. Disciplines often represented in studies include:
 - Power
 - Avionics
 - Thermal
 - Configuration and Layout
 - Structures

- Mass Properties
- Trajectory Analysis
- Operations
- Propulsion and Attitude Control
- Human Factors (optional and unique to human space flight concepts)
- Cost
- Risk

The advanced concepts process

Figure 1 shows the Mdot process used by the NASA Marshall Space Flight Center's Advanced Concepts Office for performing an advanced concept analysis of a potential future space mission or system. ("Mdot" is derived from the rocket equation – the mass flow rate.)

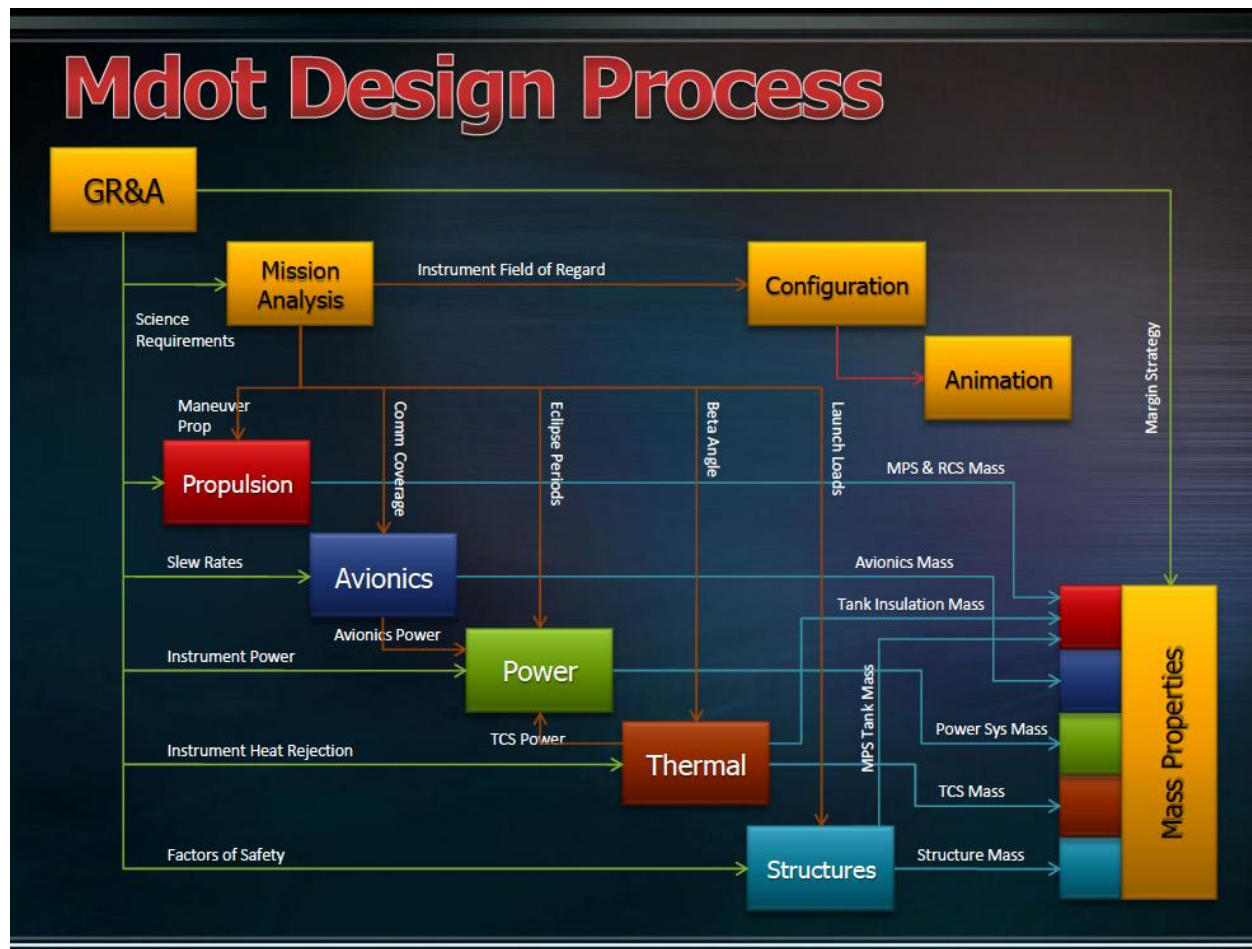


Figure 1 The advanced concepts process used by the NASA Marshall Space Flight Center.

The process usually begins with a thorough definition of the study's Ground Rules and Assumptions. It is in this phase that the customer describes the concept to be assessed or used as the basis for a mission concept definition. A cautionary note is in order: Many customers have preconceived ideas regarding how their technology might or might not be fielded and how it should or should not be implemented. Unless there is great care in the definition of the Ground Rules and Assumptions, these notions – which are really nothing more than notional engineering design solutions – might get listed as a ground rule or an assumption. This must be avoided. It is up to the advanced concept study team to address these issues and to back them up with detailed engineering analysis. Poor GR&A can ruin a concept study.

The next step is usually a first cut mission analysis, or trajectory identification, based on gross payload mass and customer-provided destination requirements. This is done to bound the problem and to make sure that it is even possible for the spacecraft under consideration to meet a customer's requirements. From this will flow general propulsion and attitude control system requirements in the form of an overall required velocity increment (ΔV). For Earth orbital missions, it is here that overall end-of-life deorbit propulsion requirements, if any, will be identified.

The propulsion system is sized to perform all of the orbital maneuvers required during the mission. These maneuvers may include initial orbit insertion, orbit altitude changes, orbit plane changes, orbit altitude maintenance. In many cases the propulsion system consists of a main propulsion system (MPS) to perform orbital maneuvers and an auxiliary reaction control system (RCS) to provide spacecraft attitude control. The design of the propulsion system depends on many parameters in addition to the mission ΔV budget. The spacecraft mass usually drives the propulsion system thrust requirements and the mission duration or number of maneuvers usually drives the propellant selection.

The avionics subsystem analysis includes the sizing of the data storage system, communications system, and control system. The avionics subsystem design is usually driven by the data quantity that is transmitted, the spacecraft distance from Earth, the required communications network, and the pointing and slew rate requirements for the spacecraft concept. One of the driving factors in sizing a spacecraft's power system is communications. If a mission is to operate far from Earth, or requires very large data rates, then this could be a significant design driver for the spacecraft's power system. It may also dictate pointing requirements, especially for missions deep in the outer solar system that require large communications antennas on the spacecraft.

The power system design is based on the electrical power requirements of the spacecraft subsystems, including the avionics, propulsion system controllers and heaters to maintain proper temperatures for spacecraft systems. For human missions, power must also be supplied to life support systems. Electrical power is usually produced by solar arrays attached to the spacecraft. The amount of power generated is dependent on the size of the solar arrays and the angle between the sun and the solar array, which usually depends on the orbital plane of the spacecraft. The power system design is often complicated due to the fact that a spacecraft in low Earth orbit will spend considerable time in the shadow of the Earth. The power system must therefore be sized to produce more than enough power during the sunlit portions of the orbit and send the excess power to an electrical storage system capable of delivering power when the spacecraft cannot use solar power.

The thermal control subsystem design is based on a comprehensive analysis of the thermal balance of the on-orbit environment; heat generated by spacecraft systems and the temperature requirements of the spacecraft. The spacecraft must be shielded from the radiated heat of the sun and insulated from the extreme cold in shadows. The heat generated by the spacecraft electrical system must also be dissipated to maintain proper operation temperatures. The thermal control system usually consists of thermal insulation covering the external surfaces of the spacecraft, electrical heaters to maintain equipment temperatures and thermal radiators to prevent excess heat build-up.

The spacecraft structural design is based on the configuration requirements of the spacecraft and analysis of the structural loads placed on the spacecraft. The configuration is dependent on many factors, such as placement of scientific sensors, placement of solar arrays, propulsion system size and in the case of human missions, crew system layout. In many cases the most significant configuration driver

is the packaging of the spacecraft in the launch vehicle payload shroud. The structural loads are usually greatest during the launch and ascent to orbit. The spacecraft structures must have sufficient strength and stiffness to withstand the acceleration loads and vibrations during launch.

“I have an idea!”

The first essential step for assessing a new concept is to answer the question, what is the need? Many technologists are so enamored with their innovation that they fail to understand that no one will support it if it doesn't meet someone's needs. It is best to discuss or describe the innovation by its functionality and mission-level impact taking into account as many anticipated system-level impacts as possible – as identified in a thorough advanced concepts analysis.

For example, a new technology for producing abundant power in deep space seems like the kind of innovation that would be of interest to anyone considering missions into deep space. However, for many robotic science missions it is not necessarily advantageous to have more power as there may not be any science instruments with such a requirement. If an entirely new paradigm, infrastructure, and instrument technology base is required to use the new power source then it may not be cost effective to implement, even if a potential customer were to sufficiently understand and appreciate how it might benefit their research.

In the case of a new power system that significantly increases the power availability in deep space, an advanced concepts analysis would also have to be performed to fully understand the system level impact of the new technology on the rest of the spacecraft. Some questions to be asked include:

1. How will the spacecraft get rid of the extra heat load?

- a. Typically, more radiators will be required, increasing both the weight and cost of the spacecraft, not to mention its increased complexity.
2. Will any spacecraft and payload science instruments consider the new power source as a new background noise?
 - a. Science instruments can be sensitive to background electromagnetic (EM) radiation, in which case they may be adversely effected by the additional EM radiation from the new, high power system.
3. Are there safety issues with launching the new power source?
 - a. Any sufficiently compact, high-density power source miniaturized to fit within a spacecraft is only a small step away from being an explosive with clearly associated mission risks.

“How do I get it selected for flight?”

There are many good ideas out there for space missions, whether they are in space science, exploration or advanced technology development. Unfortunately, there is always limited funding. The shortage of money therefore drives the bureaucratic system of most governments into having a standard processes by which missions and technologies are selected for flight. Learning these processes is vital to the advanced concept advocate.

Most people think that winning a flight happens as the result of writing a good proposal once a government solicitation is released. While this is strictly true, it does not tell the whole story. In fact, while a good proposal is necessary to win, it is, by itself, woefully insufficient. Most proposals are actually sold before the proposal is ever written. To be successful, the offerors should consider a variation to this plan of action before the date of a solicitation is even announced:

1. Make your idea widely known by presenting it at technical conferences and in journals.

2. Attend the discipline specific meetings held by the potential customers and advocates, presenting your idea, even if the conference's topic is not something directly related to your primary interests. An example might be a small spacecraft manufacturer who conducted an internal study of using a new attitude control algorithm for their spacecraft bus attending a gathering of solar physicists because the manufacturer knows that such a pointing stability will be of significance in future solar physics science missions.
3. Find out who the deciding official will be for an expected procurement, and go visit with him or her, discussing your great new idea, before the procurement is ever released. Your goal is to influence the procurement so that your idea is absolutely within its scope.
4. Find other potential users, even those who may not have any money to fund it at this time, and get letters of interest or support for use in upcoming competitive solicitations.
5. Repeat steps 1 to 4, as necessary, until the selection and funding of your idea.
6. In parallel to the above, partner with industry, academia, or even a government agency to broaden the political and technical support for your idea. Having internal champions within the sponsoring organization significantly increases your odds of being selected.
7. With your Step 6 partners, complete a high-level mission concept study that will allow you to have graphic images or even artist depictions of your idea. A picture is worth a thousand words, but an engineering drawing is worth at least getting to TRL-6 with a shot at TRL-7.
8. Don't oversell. Be honest in your trade studies when it comes to the pros and cons of your ideas versus the competition. Just make sure you highlight the pros and have a good answer to the cons – good, in the sense that you have a plan to attack whatever the problem may be.
9. When the solicitation is released, don't go after it alone. Yes, you and your organization may be the best people in the world to do the work, but partnering with others provides enhanced advocacy and a sense of the idea's importance.

10. Get ready to lose; but in the loss, find out from the reviewers what needs improvement so that you will become better prepared for the next opportunity.

Crossing the TRL Valley of Death

The problem of insufficient technical readiness can prevent missions from using new technologies, thus reducing potential returns, and the subsequent entrapment of new technologies without sufficient flight validation to reduce their inherent risk – potentially ‘forever’ preventing the new technology or approach from being selected for a flight mission. Many technologies find themselves at this critical juncture, known as the TRL Valley of Death, because they are too advanced for further ground-based research and development, yet have been insufficiently proven to be accepted for a flagship science or exploration mission because they have never before been proven in space.

The Valley of Death exists because of the inherent high cost of flying missions in space. The cost of maturing most space technologies from one TRL to the next is relatively inexpensive when compared to the cost of going from TRL-6 to 7. In fact, for many technologies the cost of going this last step is far more than all the money spent to take them from TRL-1 to TRL-6 combined.

Advanced Concepts Analysis in Technology Selection

A good advanced concepts analysis should result in a spacecraft or vehicle concept that will eventually be proven to have been within 30% of its eventual mass and cost. While not a detailed design, concept analysis will nonetheless provide a configuration, mission scenario, spacecraft or vehicle configuration, mass and power budgets, materials list and integrated mass table (with margin), and a candidate launch vehicle capable of lofting the payload to its desired destination.

Within aerospace generally, advanced concepts analysis is used in a wide-range of areas, including the following examples. **Future Space Missions:** Mission design includes defining outcomes, designing for the mission environment, planning for mission ground support, and considering follow-on missions. As with spacecraft design, mission design must consider end-to-end planning, from the initial funding to the system's retirement: system costs, operational needs, hardware and software interactions, mid-mission problem-solving, and hardware disposal. Advanced concepts analysis digs down to the component level of design, but also takes the "50,000-foot" view to ensure that a human or robotic mission operates in the way it was intended. **Space Transportation Concepts:** Starting from the ground up, space transportation systems must be considered from liftoff, to in-space operations, to atmospheric entry. When Advanced Concepts conducts planning for space transportation systems, all aspects of the work must be considered, from propellant use to propulsion system mass and performance to payload interfaces. This sort of preliminary planning ensures that hardware traveling into and through space is optimal for its intended mission, and that it can function properly when it arrives at its destination. **Launch Vehicle Concept Design:** Launch vehicles are defined to ensure that payloads of a specific weight reach the proper altitude above the Earth. A thorough definition process will include reviews of current, in-work, and theoretical designs for space missions to ensure that a launch vehicle design is optimized to meet a particular class, or classes of mission's needs. Using the industry standard and organization unique models (when they exist), the analysis should evaluate the safety and success of the vehicles that take space missions from the ground into space. **Integrated Space Systems Analysis and Design:** Whether it be a life support system, a vehicle, or a mission requiring multiple pieces of hardware and software, analysis of the interactions between multiple systems and subsystems will help mission planners make informed decisions about future designs. The analysis should anticipate problems before they appear in the hardware allowing for major

incompatibilities to be remedied in the relatively inexpensive concept definition and design phase of a project.

Conclusion

A successful advanced concept analysis team looks like a miniature engineering organization in terms of skill mix and like an integrated product team in terms of staffing. It must be small, experienced in working at a fairly high level (in other words, not so detail oriented as to preclude the ability to produce rapid turnaround engineering analyses with accuracies of about a factor of two), and able to iterate many different concept design options rapidly.

Team analysis must begin by gaining a thorough understanding of mission need, and establish a close working relationship with the customer to make sure the final concept is aligned with both their stated and unstated requirements.

Finally, the team must have enough project experience to understand the difference between paper-study feasibility and engineering capability. TRL is one of the tools that can be used to make this assessment. However, there is no substitute for experience, and having a team populated with engineers who have worked on a hardware project in the past is a definite advantage, and tends to produce a more realistic advanced concept design.

Case Study

There are numerous examples of successful advanced concepts studies available in the literature. An example of one led by the authors of this chapter is provided below.

Integrated In-Space Transportation Plan

Advanced In-Space Propulsion (ISP) technologies will enable much more effective exploration of our solar system, and will permit mission designers to plan missions to "fly anytime, anywhere and complete a host of science objectives at the destinations" with greater reliability and safety. When compared with state-of-the-art chemical propulsion, increased capabilities include shorter trip times to outer planets, higher payload mass, and enabling of missions, which are very difficult or impossible with chemical propulsion. Examples of these missions are orbits around the outer planets, interstellar probes, and sample return missions from Mars or other planets. With a wide range of possible missions and many candidate propulsion technologies with very diverse characteristics, the question of which technologies are "best" for future missions, is a difficult one. Resource limitations do not permit the development of all candidate propulsion technologies. Therefore, it is required to develop a set of propulsion technologies that will adequately satisfy a broad spectrum of mission requirements.

In the early 2000's, NASA tasked the NASA Marshall Space Flight Center to lead a national effort to identify promising ISP technologies, assess their ultimate capability to perform various future science and exploration missions, and recommend which should be funded for further development.

The effort was broken down into five parts: (1) address missions, mission priorities, and mission requirements as defined by the various NASA mission directorates; (2) provide a forum for technologists to advocate any ISP technology for any mission(s) for which they deemed their propulsion technology to be appropriate; (3) perform system analyses of the prioritized mission set to the degree necessary to support evaluation and prioritization of each technology advocated by the technologists; (4) perform cost analyses on each of the technologies that were determined by systems analyses to be viable

candidates for the mission set; and (5) integrate all customer, technologist, systems, cost, and program inputs into a final prioritized set of technologies.

The primary products were a prioritized set of advanced ISP technologies that meet customer-provided requirements for the customer prioritized mission set and a set of recommendations of relative technology payoffs to guide future NASA investment decisions. This effort involved many people at most NASA centers. The effort was divided among several teams,

- The **Missions Requirements Team** (MRT) defined the missions of interest and established the requirements for each.
- The **Systems Team** (ST) performed systems analyses to derive the important mission parameters for each propulsion technology for each mission. The ST also scored each technology for each mission against the figures of merit for performance, technical, and reliability/safety. The team consisted of 25 people from six NASA centers and three private companies.
- The **Technology Team** (TT) proposed candidate propulsion technologies to be applied to each of the missions and provided the important performance and technical characteristics for each of the proposed technologies. The TT also performed scoring for figures of merit related to schedule. The team consisted of 22 people from five NASA centers and two private companies.
- The **Cost Team** (CT) performed cost analyses and performed scoring on figures of merit related to cost. The team consisted of four people from two NASA centers and two private companies.
- An **Advisory Group** (AG) performed oversight for the entire process. The group reviewed the mission selection, reviewed the figure of merit (FOM) Dictionary, set weights for figures

of merit within each figure of merit category, set weights among the figure of merit categories, and performed the final prioritization from the data derived and presented. The group consisted of nine people from NASA Headquarters and three NASA centers.

The Mission Requirements Team identified 28 missions of interest to NASA. These missions were allocated to one of nine different mission categories, according to mission destination and propulsion function at the destination (see Table 1). As available time and resources did not permit detailed analyses of all 28 missions, nine were selected on the basis of,

1. Missions rated as highest priority by the MRT;
2. Maturity and completeness of mission requirements;
3. Importance of availability of advanced propulsion technologies to the efficacy of the mission; and
4. Attainment of a representative set over a diverse range of mission requirements.

To ensure that the highest priority missions were analyzed first, the MRT prioritized missions within each mission category; italics in Table 1 denote the nine missions analyzed. For each mission analyzed, the top-level mission requirements were documented and maintained in a Requirements Document.

Mission Category	Missions of Interest
Earth vicinity, low to moderate delta velocity (ΔV)	Geospace Electrodynamics Connection (GEC)
	Low Earth Orbit Synthetic Aperture Radar (LEO SAR)
	Natural Haz. & Soil Moisture Measurement SAR
	Earth Radiative Energy Meas. Facility (Leonardo)
	<i>Magnetospheric Constellation (MC)</i>
	Ionospheric Mappers
Inner solar system, simple profile, moderate ΔV	Space Interferometry Mission (SIM)
	StarLight ST-3
Inner solar system, sample return	Comet Nucleus Sample Return (CNSR)
	<i>Mars Sample Return (MSR)</i>
Inner solar system, complex profile, moderate to high ΔV	Earth Atmospheric Solar Occultation Imager (EASI)
	<i>Pole-Sitter (PS)</i>
	Sub L1 point mission
	Solar Sentinels
	<i>Solar Polar Imager (SPI)</i>
	Next Generation Space Telescope (NGST)
	Terrestrial Planet Finder (TPF)
	Outer Zodiacal Transfer
Outer solar system, simple profile, high ΔV	Outer Zodiacal Transfer
Outer solar system, complex profile	<i>Titan Explorer (TE) (Titan Organics Orbiter/Lander)</i>
	<i>Neptune Orbiter (NO)</i>
	<i>Europa Lander (EL)</i>
	Solar Probe
Beyond outer solar system	<i>Interstellar Probe (ISP)</i>
HEDS lunar, cislunar, and Earth vicinity	Moon and Earth-Moon libration points
	Sun-Earth libration points
HEDS asteroids / Mars vicinity	Near-Earth asteroids
	<i>Mars Piloted (MP) and cargo</i>

Table 1 Future NASA Missions as High Priority Candidates for new In-Space Propulsion Technologies

The results of the study identified Aerocapture, 5 - 10 kW solar electric ion propulsion, and nuclear electric propulsion as high priority technologies. Solar sails, 100 kW solar electric hall thrusters, and advanced chemical propulsion were identified as medium priority technologies. Plasma sails, momentum exchange tethers, and low density solar sails were identified as high risk/high payoff technologies primarily due to their relatively low technical maturity.

The results of this study were used to prioritize the investments of the 200 million USD NASA In-Space Propulsion Technology Project from 2002 – 2005 that resulted in the successful maturation of aerocapture, 5 - 10 kW solar electric ion propulsion, and solar sail technologies to TRL 5/6 through extensive ground technology demonstrations.

References

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